Distortion invariant pattern recognition with phase filters

Joseph Rosen and Joseph Shamir

A recently developed approach for pattern recognition using spatial filters with reduced tolerance requirements is employed for the generation of filters containing mainly phase information. As anticipated, the recognition levels were decreased, but they remain adequate for unambiguous identification together with appreciable amounts of distortion immunity. Furthermore, the information content of the filters is compatible with low resolution devices like spatial light modulators.

I. Introduction

In a recent publication[1] a new general procedure was introduced that may be employed for generating spatial filters with reduced resolution requirements. The viability of the procedure was demonstrated by generating bipolar amplitude filters to perform rotation invariant pattern recognition.[2] It is well known, however, that the phase information contained in the Fourier transform domain is very important, and efficient pattern recognition was achieved using phase-only matched filters (POFs).[3–5]

In this work we show that the new procedure is applicable also for the generation of phase filters with reduced resolution requirements and capable of implementing distortion tolerant pattern recognition.

The next section describes the procedures for generating a modified phase-only filter (MPOF) and its incorporation into a composite phase filter (CPF). Computer experiments demonstrate the performance of these filters and their advantages for various applications.

II. Filter Functions

In pattern recognition systems the usual objective is the construction of N spatial filters that can recognize each pattern in a given set of N patterns, $f_i(x,y)$, $(i = 1,2,\ldots,N)$. To perform this task in a shift invariant manner we form their 2-D Fourier transform (FT), $F_i(u,v)$, and evaluate the transfer characteristics of the N filters $M_j(u,v)$, $(j = 1,2,\ldots,N)$ to be placed in the FT plane. A generalized system response may be represented schematically by the relation

$$\mathbf{R}_{ij} = \mathbf{Q}[F_i(u,v);M_j(u,v)] = \delta_{ij}, \quad (1)$$

where $\mathbf{Q}$ is some operator. In the present work we define the operation by the requirement that the output distribution of a simple spatial filtering configuration (Fig. 1) vanishes at the origin for an unmatched pattern. The amplitude distribution over the output plane is given by

$$O_{ij}(x,y) = \mathcal{F} F_i(u,v)M_j(u,v), \quad (2)$$

and our requirement (1) concerns its intensity at the origin of the output plane given by

$$|\int F_i(u,v)M_j(u,v)dudv| = \delta_{ij}. \quad (3)$$

The satisfaction of this criterion was also the goal in the example of Refs. 1 and 2, and it was implemented by using real bipolar filters. It was also indicated there that in a practical case Eq. (3) must be augmented by additional constraints on other points in the vicinity of the origin.

Recalling the high efficiency and selectivity obtained with phase-only filters[4] the objective of this work is to use the phase information contained in the FT of the input patterns as the basic contributor for generating the filters. Thus we would like to exploit the advantages of POFs retaining the prime objectives of this research, i.e., the generation of filters with relatively low information content that are at least partially tolerant for object distortions.

We start by separating the Fourier plane distribution of the input patterns into their magnitude and phase:

$$F_i(u,v) = |F_i(u,v)| \exp j\phi_i(u,v). \quad (4)$$

The authors are with Technion—Israel Institute of Technology, Department of Electrical Engineering, Haifa 32000, Israel.
Received 1 December 1986.
0003-6935/87/122315-05$02.00/0.

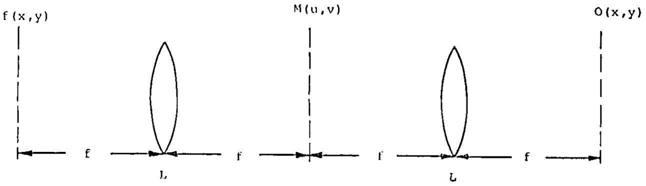

Fig. 1. Optical system considered for spatial filtering.

A phase-only matched filter to recognize pattern $f_i(x,y)$ would have a filter transfer function given by

$$M_i(u,v) = \exp - j\phi_i(u,v). \quad (5)$$

As shown in Ref. 2 a completely rotation invariant filter would have circular symmetry, i.e., the filter function should somehow be averaged over the whole circle. Considering the phase function in Eq. (4) one should perform such averages very carefully, since, at least for real inputs, one has

$$\phi(u,v) = -\phi(-u,-v) \quad (6)$$

that may lead to the loss of all relevant information. This indicates partial rotation invariance should be much easier to attain than complete rotation invariance. An additional consideration should take into account that the phase variation is usually much more rapid than the amplitude variation, and it is repetitive between two values. Thus during the sampling process required for computer generation of the filters the sampling regions should be carefully controlled by satisfying the Nyquist criterion at least for part of the filter plane.

To proceed with implementation of a partially rotation invariant filter we follow the outline of Ref. 1 and sample the Fourier plane along K concentric rings. The number K is chosen to satisfy the Nyquist criterion for the phase function $\phi(u,v)$. Denoting by α the required degree of rotation invariance we split the Fourier plane into $L = 2\pi/\alpha$ sectors producing altogether $K \times L$ regions, each of area s_{kl}, where $k = 1,2,\ldots,K$ and $l = 1,2,\ldots,L$. In the final filter that is supposed to recognize pattern $f_j(x,y)$, each of these regions will have a constant, in general complex, transmittance M_{jkl}, and our task is to determine these values to satisfy Eq. (3) as nearly as possible.

Various procedures may be used toward achieving our goal. Here we report one approach that starts with a modified phase-only filter (MPOF) that contains weighted samples of the phase function. Defining a complex matrix by the relation

$$V_{jkl} = \frac{\int_{s_{kl}} |F_j(u,v)| \exp - j\phi_j(u,v) du dv}{\int_{s_{kl}} |F_j(u,v)| du dv}, \quad (7)$$

we evaluate the phase of each element by the relation

$$\phi_{jkl} = \arctan \frac{\int_{s_{kl}} |F_j(u,v)| \sin\phi_j(u,v) du dv}{\int_{s_{kl}} |F_j(u,v)| \cos\phi_j(u,v) du dv} \quad (8)$$

and assign it as the transmission phase shift for the k,lth region in the MPOF matched to pattern $f_j(x,y)$. Thus a filter $H_j(u,v)$ with the samples of its transfer function given by

$$H_{jkl} = \exp j\phi_{jkl} \quad (9)$$

may serve as a partially rotation invariant pattern recognition filter.

Like the regular POF this MPOF is also as light efficient, but there is no *a priori* guarantee that it satisfies Eq. (3). To approach that goal we proceed following Ref. 1 and construct a composite filter[6] for the N patterns to be treated:

$$M_j(u,v) = \sum_{n=1}^{N} a_{jn} H_n(u,v), \quad (10)$$

where H_n are the filter functions with samples given by Eq. (9) and a_{jn} are constants to be evaluated after substitution in an equation of the form of Eq. (3):

$$\left| \int F_i(u,v) \sum_{n}^{N} a_{jn} H_n(u,v) du dv \right| = \delta_{ij}, \quad (11)$$

or, written in a more convenient way,

$$\left| \sum_{n}^{N} a_{jn} \int F_i(u,v) H_n(u,v) du dv \right| = \delta_{ij}. \quad (12)$$

In principle this composite phase filter (CPF) should perform better than the MPOF. It must be pointed out, however, that the CPF is no longer a phase-only filter, and it contains some amplitude variations too. Therefore, we lose partially one of the advantages of phase-only filters, i.e., the high transmission efficiency.

III. Experiment

At the present stage, the experimental work consisted of computer simulations where the performances of four kinds of filter were compared: the regular matched filter (MF); the phase-only matched filter (POF); the modified phase-only matched filter (MPOF); and the composite phase filter (CPF).

Experiments were performed with various arbitrary shapes, with single letters and with complete words, some of which are described below. In the experiments described here four names served as input patterns, and filters were generated to recognize one of them. Three of the names contained in one experiment are shown in Fig. 2. Filters were made to recognize RONA, which appears in the figure also slightly distorted. Figure 3 is the output distribution for a regular MF, while Fig. 4 is the output distribution for a POF. Neither filter could recognize the distorted pattern. The dramatic narrowing of the recognition peak for the POF is actually a hindrance for distortion tolerance. In fact, the name ANAT that has some features in common with RONA (NA) had a better correlation peak than the distorted RONA.

To construct the MPOF the filter plane was divided initially into $K = 64$ rings and $L = 4$ sectors to yield relatively high rotation tolerance. Thus the total number of samples in the filter plane was 256, well

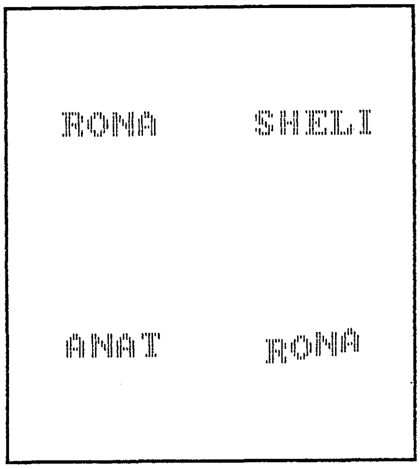

Fig. 2. Input pattern from which the name RONA should be recognized.

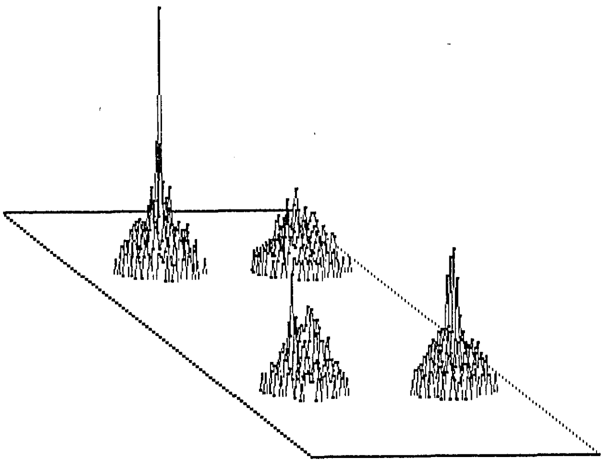

Fig. 3. Output distribution for regular MF prepared for RONA.

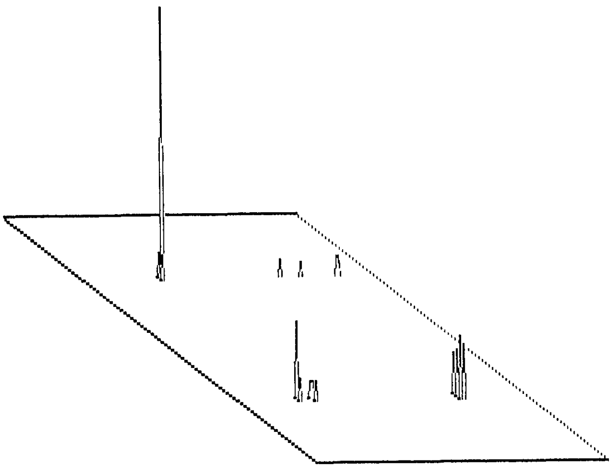

Fig. 4. As Fig. 3 but with a POF.

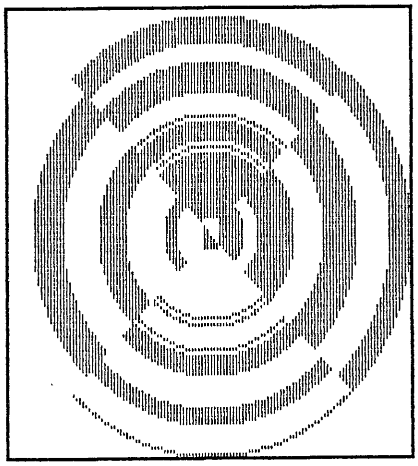

Fig. 5. Approximate representation of the phase distribution over the MPOF.

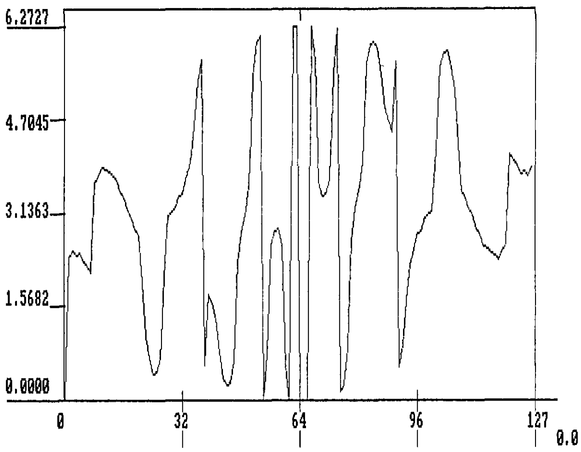

Fig. 6. Phase scan along one diameter of Fig. 5.

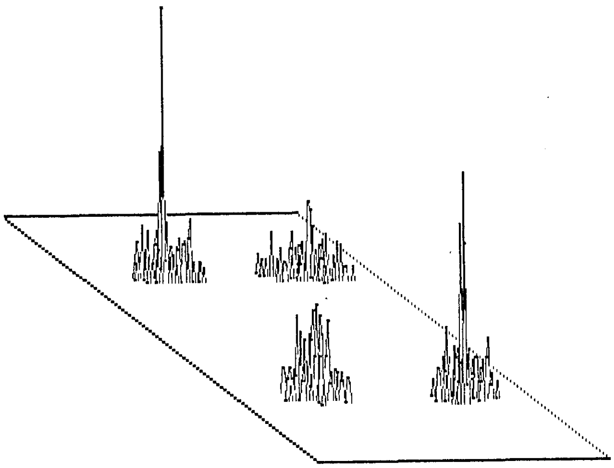

Fig. 7. As Fig. 3 but with the MPOF of Figs. 5 and 6.

within the capabilities of spatial light modulators. The number of patterns treated in each experiment was usually $N = 4$. An MPOF to recognize RONA was generated according to Eq. (8) with its phase distribution over the complete plane shown qualitatively in Fig. 5, while an exact scan through one diameter is plotted in Fig. 6. The employment of this filter for Fig. 2 gives the intensity distribution of Fig. 7. The selectivity of this filter is comparable with the regular

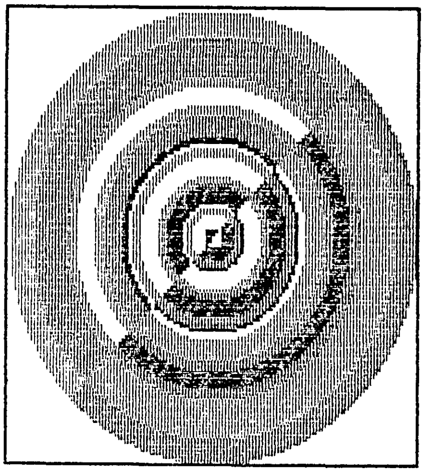

Fig. 8. As Fig. 5 but for a two-sector MPOF.

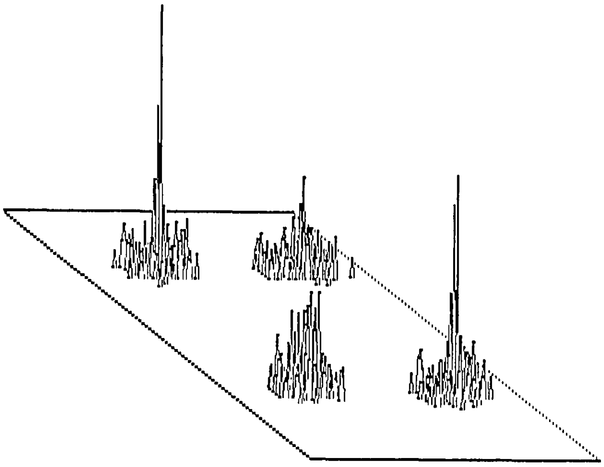

Fig. 9. As Fig. 3 but with the MPOF of Fig. 8.

MF and is less than that of the POF. The distorted pattern is detected with a peak intensity level of height situated midway between that of the original pattern and that of a false peak. A reduction of L to 2 for more rotation tolerance (Fig. 8) had no appreciable effect (Fig. 9), but a reduction of K to 21 resulted already in an increased false detection (Fig. 10).

Returning to $K = 64$ and $L = 4$ the rotation invariance of the MPOF was investigated for larger rotations where the MF and POF are completely useless. Figure 11 is the input to be processed with an MPOF prepared for RON. The output distribution is shown in Fig. 12 with a quite good detection level (height of correlation peak) for the object rotated by 30°. Nevertheless, this level approaches the false alarm level that makes identification questionable.

To improve performance a CPF was generated according to Eqs. (8)–(12) as shown in Fig. 13. The false alarm was appreciably reduced retaining the relative detection level unaffected (Fig. 14). The price paid for this improvement is a reduction in light efficiency compared to the POF or MPOF but is still better than for the MF.

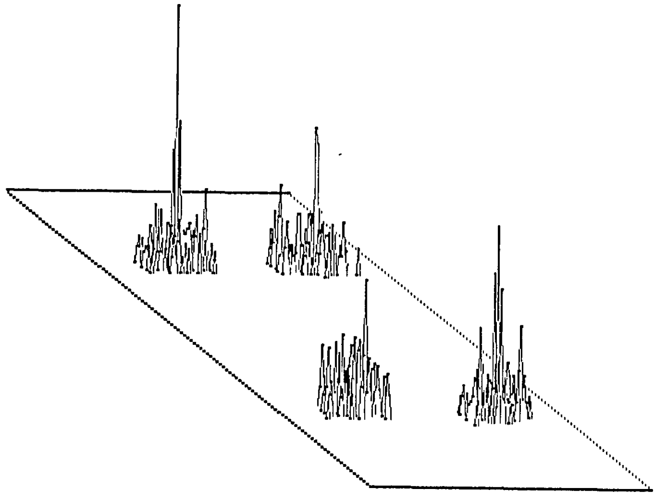

Fig. 10. As Fig. 3 but with a four-sector twenty-one-ring MPOF.

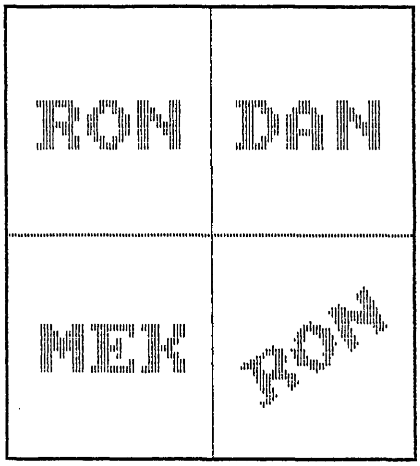

Fig. 11. Input pattern for second set of experiments.

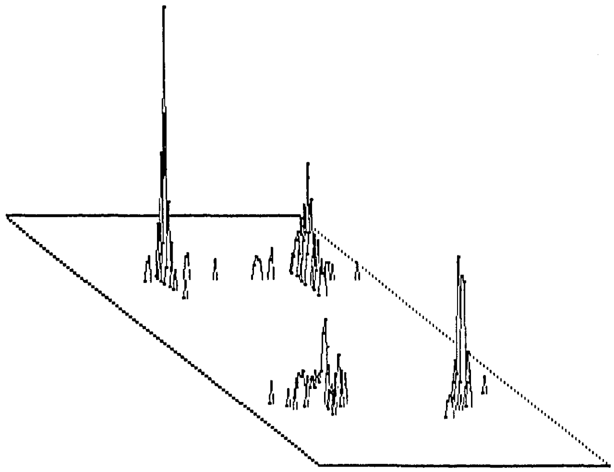

Fig. 12. Output pattern for an MPOF prepared to recognize RON.

From the above experiments a comparison can be made among the various filters considering the SNR as a function of object rotation. Figure 15 is a qualitative plot for the four kinds of filter as measured in the

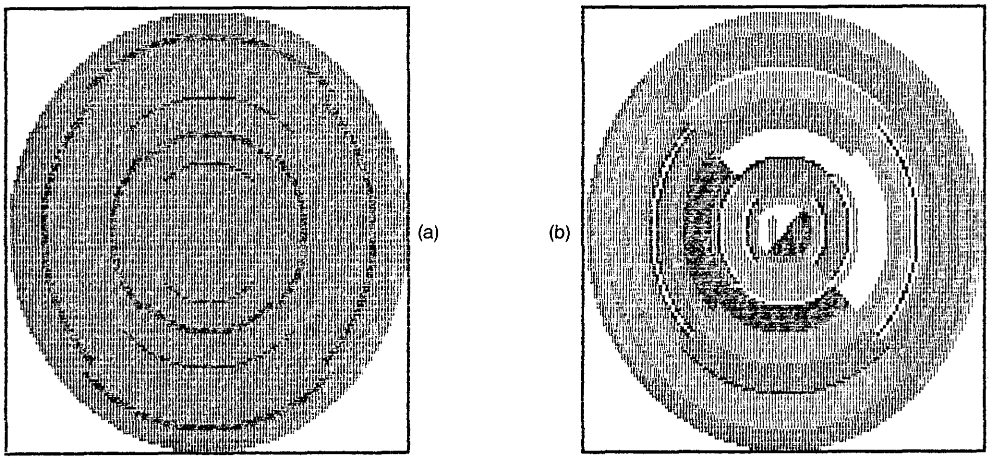

Fig. 13. CPF to recognize RON: (a) amplitude distribution; (b) phase distribution.

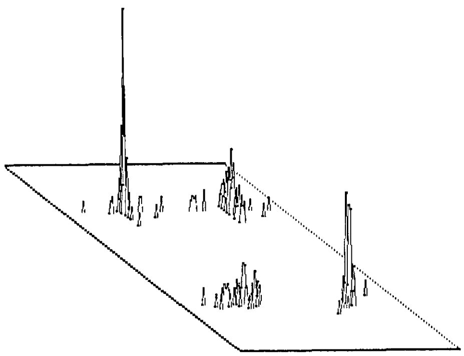

Fig. 14. Output pattern of Fig. 11 filtered with the CPF of Fig. 13.

experiments. The SNR is defined as the peak intensity level relative to the level of the highest false alarms. The superior performance of the CPF (b) with respect to distortion tolerance is evident, although, as expected, the POF has the highest detection level for undistorted patterns.

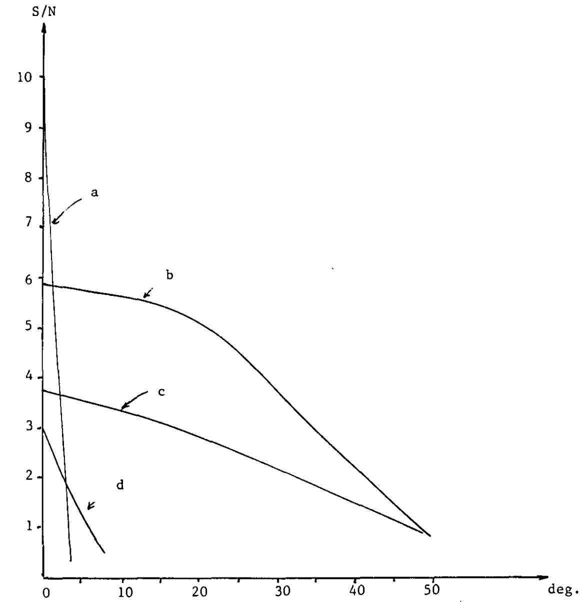

Fig. 15. Qualitative comparison of the performance for four filters as estimated from the above experiments: (a) POF; (b) CPF; (c) MPOF; (d) MF.

IV. Conclusions

In this work we introduced a new kind of phase-only filter, the modified phase-only filter that indicates an appreciable distortion immunity. The selectivity of these filters was improved by combining a number of them in the composite phase filter. The superior performance of this filter was demonstrated by computer experiments.

The generation of the CPF follows the procedures outlined in Ref. 1 to obtain filters with reduced resolution requirements on the filter and immunity to distortions. This work describes one possible way to generate the CPF, and some others are under investigation.

This work was partially supported by a contract with NASA Johnson Space Center under contract NAS9-27598.

References

1. J. Shamir, H. J. Caulfield and J. Ben-Haim, "Pattern Recognition Using Reduced Information Content Filters," Appl. Opt. **26**, 000 same issue (1987).
2. J. Ben-Haim and J. Shamir, "Scale and Rotation Invariant Pattern Recognition," Proc. Soc. Photo-Opt. Instrum. Eng. **700**, 25 (1986).
3. H. J. Caulfield, "Role of the Horner Efficiency in the Optimization of Spatial Filters for Optical Pattern Recognition," Appl. Opt. **21**, 4349 (1982).
4. J. L. Horner and P. D. Gianino, "Applying the Phase-Only Filter Concept to the Synthetic Discriminant Function Correlation Filter," Appl. Opt. **24**, 851 (1985).
5. J. L. Horner and J. R. Leger, "Pattern Recognition with Binary Phase-Only Filter," Appl. Opt. **24**, 609 (1985).
6. H. J. Caulfield and W. T. Maloney, "Improved Discrimination in Optical Character Recognition," Appl. Opt. **8**, 2354 (1969).